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Landslide Stabilization Using Wick Drains

Final Report for Highway-IDEA Project 76

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EXECUTIVE SUMMARY

A method has been developed to use soil wick drains for a novel application of landslide and slope stabilization. Wick drains are flat, fabric-coated plastic channels, which were initially developed to be vertically driven into the ground using a specially adapted crane. They accelerate consolidation and settlement by an order of magnitude by significantly shortening the flowpath for water to exit a soil layer. An earlier portion of this study developed equipment to install wick drains horizontally, so that they might be used to drain landslides. The equipment was tested at several sites, and the process was shown to be quick, inexpensive, and effective at removing water from slopes. The current portion of the study completed two additional full scale installations in Missouri and Colorado, and developed and tested a pipe gripping device to streamline the installation process. In total, more than 170 drains totaling over 8600 feet in length have been installed at eight sites in Missouri, Colorado, and Indiana. Drain installation rates averaging over 60 feet per day were realized during the study, for costs estimated at approximately $2.50 per foot.

Laboratory experiments to assess potential clogging of wick drains were conducted over a period of two years. These tests showed varying amounts of fine particles coating the inside strands of the drain fabric. However, these particles did not seem to affect the drain's ability to transmit water.

Finally, a procedure was developed to estimate the shape of the water table surface for drained landslides, using parameters easily measured in the field and laboratory, and this procedure was applied to computer slope stability analysis of two of the stabilized landslides.

Landslide Stabilization Using Wick Drains

by

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INTRODUCTION

A method has been developed to use soil wick drains for a novel application of landslide and slope stabilization. Wick drains are flat, fabric-coated plastic channels, which were initially developed to be vertically driven into the ground using a specially adapted crane. The drains are 4mm x 100mm in cross-section, and are shipped in 300m rolls. They accelerate consolidation and settlement by an order of magnitude by significantly shortening the flowpath for water to exit a soil layer (*1*). An earlier portion of this study developed equipment to install wick drains horizontally, so that they might be used to drain landslides. The equipment was tested at several sites, and the process was shown to be quick, inexpensive, and effective at removing water from slopes. The current portion of the study completed two additional full scale installations in Missouri and Colorado, and developed and tested a pipe gripping device to streamline the installation process. In total, more than 170 drains totaling over 8600 feet in length have been installed at eight sites in Missouri, Colorado, and Indiana.

Laboratory experiments to assess potential clogging of wick drains were conducted over a period of two years. These tests showed varying amounts of fine particles coating the inside strands of the drain fabric. However, these particles did not seem to affect the drain's ability to transmit water.

Finally, a procedure was developed to estimate the shape of the water table surface for drained landslides, using parameters easily measured in the field and laboratory, and this procedure was applied to computer slope stability analysis of two of the stabilized landslides.

WORK COMPLETED UNDER PREVIOUS CONTRACT

The first contract for this project focused on developing equipment to install wick drains horizontally, installing drains at several sites with different geologic conditions and using different equipment, and disseminating technical information on the process and its advantages. The following tasks were completed to address these goals:

1. A test embankment was constructed, instrumented, and stabilized. We conducted two simulated rainfall events on the embankment, and results showed that the wick drains were effective in lowering ground-water levels and reducing overall settlement. The results of these tests were presented at the annual meeting of the Association of Engineering Geologists and summarized in a Master's thesis.

2. Next, we installed wick drains in seven roadway landslides (two near Boonville and St. Joseph, Missouri, one near Rio Blanco, Colorado, two near Meeker, Colorado, one near Rye, Colorado, and one near Jasper, Indiana). The work near Jasper, Indiana was considered a full-scale stabilization, consisting of 44 drains totaling 2613 feet in length. The effectiveness of the drains at all sites was confirmed by several years of monitoring of water drainage from the wicks, resistance of the wicks to clogging or deterioration, and reduced movement of the landslides. An overview of the drain installation process and the landslide work through October 2000 was published in June 2001 in Civil

Engineering magazine and a technical paper was published in Transportation Research Record 1757.

3. Prepared and distributed over 60 copies of a demonstration video showing the process and equipment involved in the horizontal installation of wick drains.

4. Established relationships with two wick drain manufacturers and several state DOT's for current and potential future application of this technology.

WORK COMPLETED UNDER CURRENT CONTRACT

The goals of the current research contract were to complete and test one additional equipment modification, to complete full landslide stabilizations at two sites, and to finish and analysis the ongoing wick drainage and clogging experiments.

Modifications, Enhancements, and New Techniques for Drain Installation

The most significant installation problem encountered during the early part of the research was the tendency of the drive pipe to bend or buckle during pushing. This tendency has been successfully counteracted by placement of supporting landscape timbers below the pipe (Figure 1), or held in a "V" to support the pipe during driving (Figure 2). It is our conclusion that this problem has been effectively addressed by these methods.

Analysis of Water Table Surface

In order to develop accurate computer models for slope stability of drained landslides, an accurate assessment of the shape of the water table surface is important. Alternatively, an accurate picture of the water table surface is needed to properly design and space drains before installation. The difficulty in modeling the water table surface in drained landslides is that the surface is an irregular, corrugated shape, with low troughs along the lengths of the drains, and higher ridges between drains. There have been a number of studies aimed at modeling the water table surface in these situations (Choi, 1983; Kenney, et al, 1977; Lau and Kenney, 1984; Liljegren, 2000; Nakamura, 1988; Nonveiller, 1981), but they are difficult to use because they either rely on parameters that are difficult to measure, they are too complex for widespread use, or they assume a level of homogeneity of the landslide soils that is unrealistic and inaccurate.

As a consequence, one of the goals of this study was to develop a method of estimating the water table surface, using easily measured parameters, and presented in a format that would not be intimidating for most users. The method contains four steps, which are described in more detail below. In general, the objective of the method is to convert the irregular water table surface and the irregular spacing of fanned drains into an average value of each, so that slope stability analysis of a single cross-section better represents conditions across the slope as a whole.

First, inhomogeneity of drain spacing was handled by calculating the average spacing for 10-foot intervals up the axis of the landslide, as shown on Figure 3. In this way, users are free to install drains where access is good and to install additional drains where water seems to be concentrated, and then to properly calculate the effects of the drains using the average spacing.

Second, the shape of the water table along the length of an individual drain was observed using four laboratory boxes containing wick drains in soil and several piezometers along the length of the drains (Figure 4). These observations demonstrated that the water table coincided with the drain along most of its length, except at the deep end of the drain. The departure of the water table from the drain increased with increasing water percolation through soil above the drain (Figure 5).

Third, the shape of the water table between drains was calculated based on work by Hooghoudt (original work in Dutch) summarized in Luthin (1966), describing water levels between agricultural drains. In simplest terms, the relationship between drain spacing, soil characteristics, and the height of the water table may be expressed as:

$$S^2 = \frac{4KH}{v}(2d + H)$$

where:

S = drain spacing

K = soil hydraulic conductivity

H = maximum height of the water table above the profile determined in step two. This value occurs at the midpoint between two drains

v = recharge rate (estimated as the average rate of water flow from the drains)

d = depth to bedrock, adjusted by an equivalency factor

Fourth, the corrugated surface between drains described in step 3 was converted to an average water table height above the drain by integrating the equation above (adjusted for proper limits of integration), and dividing the resulting area by the spacing between drains. We are currently developing design charts to express the average water table height based on the factors used in the above equation. A approximate solution to estimate the average water table height, H^{avg}, is

$$H_{avg} = \pi \frac{s}{8}\sqrt{\frac{v}{K}} - d$$

This method will be described in detail in a Master's thesis in progress and in paper to be submitted to the journal Environmental and Engineering Geoscience in May 2002.

Clogging and Deterioration Studies

In August 1999 an experiment was set up consisting of a plexiglass tank containing two wick drains surrounded by clayey soil (Figure 6). One of the drains had a one-inch thick sand filter completely surrounding the drain and preventing contact between the drain filter fabric and the clay particles. The clay was then saturated under a constant head of water, and water was allowed to percolate through the clay, into the drains, and then to exit the apparatus where the drains exited the tank. In October 2001, approximately 26 months after initiation, the experiment was stopped and the drains were exhumed for observation. Figure 7 shows new wick drain material that has never been in contact with soil. Figure 8, of wick drain material in direct contact with clay, shows packed particles in the drain strands on the outside of the fabric, but almost no particles on the inside of the fabric. Figure 9, of wick drain material protected by a sand filter, shows only a few coarse sand grains on the outside of the fabric, and almost no particles on the inside of the fabric. These photographs demonstrate that while the sand filter prevents clogging on the outside of the fabric, the fabric itself is sufficient to prevent particles from migrating to the inside of the fabric and reduce water flow. Because the inside of the fabric is clean in both cases, one may conclude that a sand filter is not necessary to restrict particle migration to the core of the wick drain.

This conclusion is contradicted by Figure 10, which shows wick drain filter from drains installed in June 1999 near Meeker, Colorado and exhumed in June 2001. In this case, fine particles coat the fabric strands on both the outside and inside of the wick drain. This is likely a result of the longer length of this drain compared to the laboratory tests, carrying very muddy water. In spite of this, the drain still successfully produced water, indicating that the fine particles did not clog the drain or preclude water transmission by the drain.

Pipe Gripping Device

A pipe gripping mechanism was built consisting of a split steel cone (a "collet") that will automatically grip the drive pipe when pushed against a conical hole in a steel block, shown on Figure 11. The mechanism was attached to both a backhoe and a motor grader, and pipe was successfully pushed 20 and 40 feet, respectively (these depths corresponded with the maximum thicknesses of soil at the test sites, so greater depths can be reached where bedrock is deeper). Photographs of the testing are shown on Figures 12 and 13. The gripping device eliminates the problem of pipe buckling during pushing, it accelerates the installation process, and it allows use of different equipment than demonstrated previously to install horizontal wick drains.

Boonville, Missouri Landslide Stabilization

On May 21 through 25, 2001, 36 drains totaling 1832 feet in length were installed at the Boonville landslide, as shown on Figure 14. This landslide is located along Interstate 70 near the SH 5 exit, and is described in detail in the report for the first phase of this project (Santi and Elifrits, 2001). The installation was done with a Case 580 Super L Extendahoe, which is the smallest equipment used yet to push in horizontal wick drains, yet the maximum capacity of the machine was never reached, even for drains exceeding 80 feet in length. Several of the drains immediately produced water, and several others began draining after a few days.

The average drain length at this site, slightly over 50 feet, was less than desired, because a layer of rock rubble fill within the roadway embankment stopped many of the drains. The location of this rock at the surface, which mimics its presence at depth, is shown on Figure 14.

Computer slope stability analysis was conducted for the Boonville landslide, using topography and stratigraphy developed during field mapping and from boreholes, strength and density values from laboratory tests and standard references, and water table elevations from site piezometers and from the modeling process described earlier. Sensitivity analysis and back-calculation procedures were run on the current slope configuration and on the projected pre-failure slope topography, in order to validate the strength values used in the analysis and to estimate water table elevations required to initiate slope movement. Next, three additional analyses were run to demonstrate the effects of the wick drains:

1. *Stability of the slope under normal ground-water conditions.* Figure 15 shows the results of the analysis under typical conditions with a low ground-water table, producing a factor of safety against sliding of 1.14.

2. *Stability of the slope under high ground-water conditions.* Figure 16 shows the ground-water levels required to initiate slope movement, producing a factor of safety of 0.99. These are the ground-water levels anticipated during heavy rainfall.

3. *Stability of the slope under high ground-water conditions, but after wick drain installation.* Even though the wick drains could not all be pushed past the rock rubble layer, Figure 17 shows a factor of safety of 1.08 for high ground-water conditions. This is almost a 10% increase in stability, and for the conservative analysis parameters used in this study, this

improvement is expected to substantially reduce landslide movement and resulting roadway damage.

Meeker, Colorado Landslide Stabilization

On June 4 through 7, 2001, 27 drains totaling 1891 feet in length were installed at the Meeker landslide, as shown on Figure 18. This landslide is located along SH 13, and is described in detail in the report for the first phase of this project (Santi and Elifrits, 2001). The installation was done with a Caterpillar D4C bulldozer. Twelve of the drains immediately produced water, and several others began draining after a few days.

The average drain length was over 70 feet, and most drains were stopped when bedrock was encountered. Several drains reached 100 feet, and could have been pushed further, but no more drive pipe was available.

As for the Boonville landslide, computer slope stability analysis used topography and stratigraphy developed during field mapping and from boreholes, strength and density values from laboratory tests and standard references, and water table elevations from site piezometers and from the modeling process described earlier. Sensitivity analysis and back-calculation procedures were run on the current slope configuration and on the projected pre-failure slope topography, in order to validate the strength values used in the analysis and to estimate water table elevations required to initiate slope movement. Next, three additional analyses were run to demonstrate the effects of the wick drains:

1. *Stability of the slope under normal ground-water conditions.* Figure 19 shows the results of the analysis under typical conditions with a low ground-water table, producing a factor of safety against sliding of 1.09.

2. *Stability of the slope under high ground-water conditions.* Figure 20 shows the ground-water levels required to initiate slope movement, producing a factor of safety of 1.00. These are the ground-water levels anticipated during heavy rainfall.

3. *Stability of the slope under high ground-water conditions, but after wick drain installation.* The long drains installed at the site had a significant effect on the water table surface, as shown on Figure 21. This change resulted in a factor of safety of 1.17, which is a substantial increase in stability.

DRAIN INSTALLATION RATES AND COSTS

Drain installation rates and costs are a function of the experience of the installation crew and the site geology and layout. On the whole, per foot costs will decrease and installation rates will increase for longer drains, installed from a few fan pads rather than from individual pads. The estimates of actual footage rates and costs per foot are made from the three full-scale stabilization sites, as shown in the table below:

Site	Hours Worked	Feet of Drain Installed	Rate (ft/hr)
Jasper, Indiana	54.5	2613	47.9
Boonville, Missouri	36.25	1832	50.5
Meeker, Colorado	30.6	1891	61.8

These results show continued increase in the rate of installation, as the graduate students directing the operation gained experience. A new crew supplied by the local DOT was trained at each site.

The costs for installation on this phase of the project were reduced when using a backhoe rather than a larger trackhoe excavator. An estimation may be made as follows, assuming 60 feet per hour (0.017 hours/foot):

Trackhoe and operator	= \$55/hour
Three laborers	= 3 x \$20/hour = \$60/hour
Wick drain	= \$0.50/foot (varies by volume ordered)
Drive plates	= \$2/drain (if each drain = 50 feet, then cost = \$0.04/ft)

Therefore, an estimated cost per foot is:

\$55 x 0.017 hrs/foot + \$60 x 0.017 + 0.5 + 0.04 = \$2.50/foot

If per diem fees are added to this value (approximately \$320 per day) this would add approximately \$0.67 per foot to the cost, assuming production of 480 feet per day.

The costs to purchase and develop horizontal wick installation equipment are as follows:

Purchase of 150 feet of AQ drill rod:	= \$10/foot = \$1500
Construction of drive and pulling heads:	= \$200 (estimate)
Construction of 100 drive plates	= \$100 (estimate)
Total	= \$1800

PUBLICATIONS AND PRESENTATIONS

The following publications and presentations were completed in association with this portion of the research project (additional publications for the first phase of research were itemized in Santi and Elifrits, 2001):

Santi, P.M. and Crenshaw, B.A., in preparation, "Demonstration Projects Using Wick Drains to Stabilize Landslides," Environmental and Engineering Geoscience.

Crenshaw, B.A. and Santi, P.M., in preparation, "Water Table Profiles in the Vicinity of Horizontal Drains," Environmental and Engineering Geoscience.

Crenshaw, B.A., in preparation, "Water Table Profiles in the Vicinity of Horizontal Drains," unpublished M.S. thesis, Colorado School of Mines.

Crenshaw, B.A. and Santi, P.M., 2002, "Stability Modeling of a Drained Landslide, Meeker, Colorado," Geological Society of America Rocky Mountain Conference, Cedar City, UT.

Santi, P.M., Elifrits, C.D., and Liljegren, J.A., 2001, "Horizontal Wick Drains for Landslide Stabilization," Civil Engineering, June 2001 issue, pages A1-A10.

Santi, P.M., Elifrits, C.D., and Liljegren, J.A., 2001, "Design and Installation of Horizontal Wick Drains for Landslide Stabilization," Transportation Research Record 1757, pp. 58-66.

Crenshaw, B.A. and Santi, P.M., 2001, "Water Table Profiles in the Vicinity of Horizontal Drains," Association of Engineering Geologists 44th Annual Meeting Program with Abstracts, St. Louis, MO.

PARTNERSHIPS ESTABLISHED

A number of partnerships were established with agencies and wick drain manufacturers to complete this project. During the first phase of the project, $83,519 in matching funds were generated. For the current phase of work, the following is an estimate of matching funds:

Organization	Matching Provided
Colorado Department of Transportation	$5,000* (use of CDOT bulldozer for drain installation) $7,500* (personnel to assist in traffic control and drain installation) $1,500* (personnel time for project set-up and follow-up visits)
Missouri Department of Transportation	$5,000* (personnel to assist in traffic control and drain installation) $500* (traffic control vehicles) $1,500* (personnel time for project set-up and follow-up visits)
	TOTAL = $21,000

*my estimate based on personnel time and equipment used on our project

ONGOING AND PROPOSED APPLICATIONS OF THE TECHNOLOGY

Several groups are beginning to apply horizontal wick drain technology to landslide problems. To our knowledge, they include:

1. Installation of several drains to stabilize a roadway landslide in Northern California (contact: Mr. John Duffy, CalTrans),

2. Design of a 1000-foot wick drain installed by horizontal directional drilling to stabilize a landslide bluff below a residential neighborhood in Milwaukee (to be installed in March of April

of 2002) (contact: Mr. Gary Jackson, Edward E. Gillen Company, PI is a consultant on this project),

3. Proposal to CDOT to stabilize a roadway embankment near Cimarron, Colorado (contact: Mr. Ben Arndt, Yeh and Associates, Inc.)

4. Recommendation by outside reviewer for wick drain stabilization for a landslide in Los Angeles County, California (contact: Dr. J. David Rogers, Geolith, Inc., current affiliation, University of Missouri-Rolla).

SUMMARY

During this stage of research, two additional full-scale wick drain installation efforts were completed, bringing the total to three full scale installations and five demonstration installations. Both new sites were analyzed using a computer program to calculate slope stability, incorporating an accurate depiction of the average height of the water table surface, based on methodology developed for this study. Microscope examination of wick drains that had been draining soil for over two years in both laboratory and field settings showed varying amounts of fine particles coating the inside strands of the drain fabric. However, these particles did not seem to affect the drain's ability to transmit water.

Drain installation rates averaging over 60 feet per day were realized during the study, for costs estimated at approximately $2.50 per foot.

FUTURE WORK

With the publication of two technical papers in preparation, several papers and presentations completed previously, and copies of the demonstration video on hand for potential users of this technology, the PI's feel that the research has substantially demonstrated and documented the new technology of horizontal wick drain stabilization of landslides. Future work will include advising and consulting on stabilization projects, assistance to agencies and private companies desiring to develop their own capability to install drains, and continued exploration of the possibility of launching a new company to install drains.

ACKNOWLEDGEMENTS

Funding for this work was provided by the NCHRP-IDEA Program of the Transportation Research Board, Grant NCHRP-76. Test sites were stabilized in partnership with the Missouri and Colorado Departments of Transportation.

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Santi, P.M. and Elifrits, C.D., 2001, Landslide Stabilization Using Wick Drains, Project Report Prepared for the NCHRP-IDEA Project Committee, NCHRP-IDEA Grant NCHRP-57, 42 p.

Figure 1. Control of pipe buckling by timber support from underneath.

Figure 2. Control of pipe buckling by "V" support.

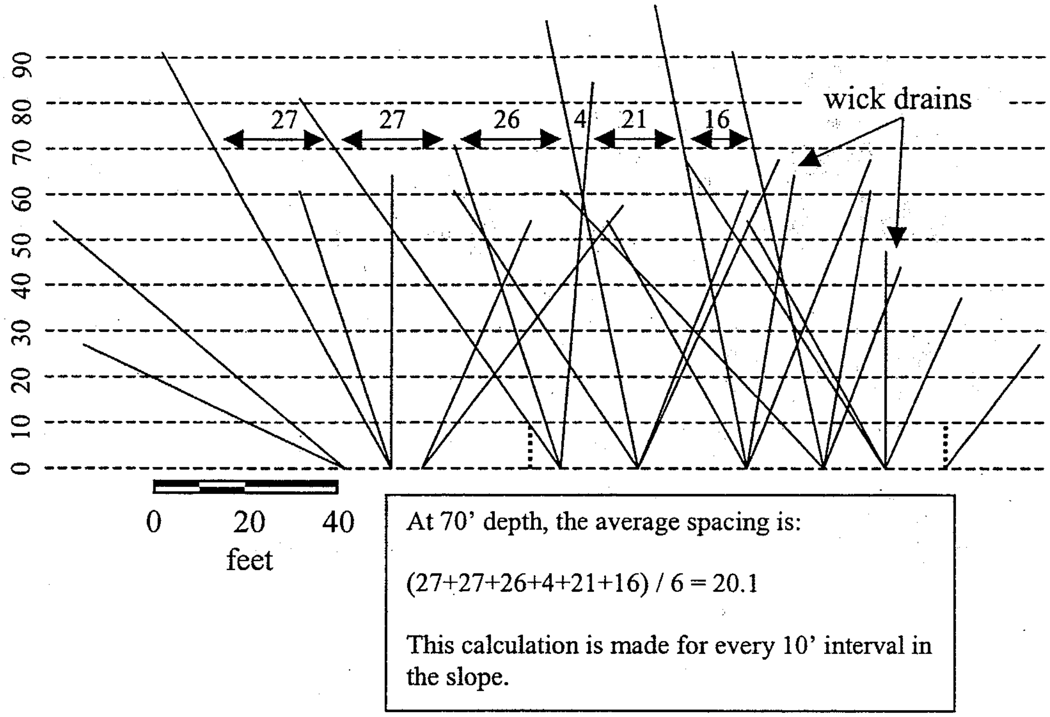

Figure 3. Example calculation of average drain spacing.

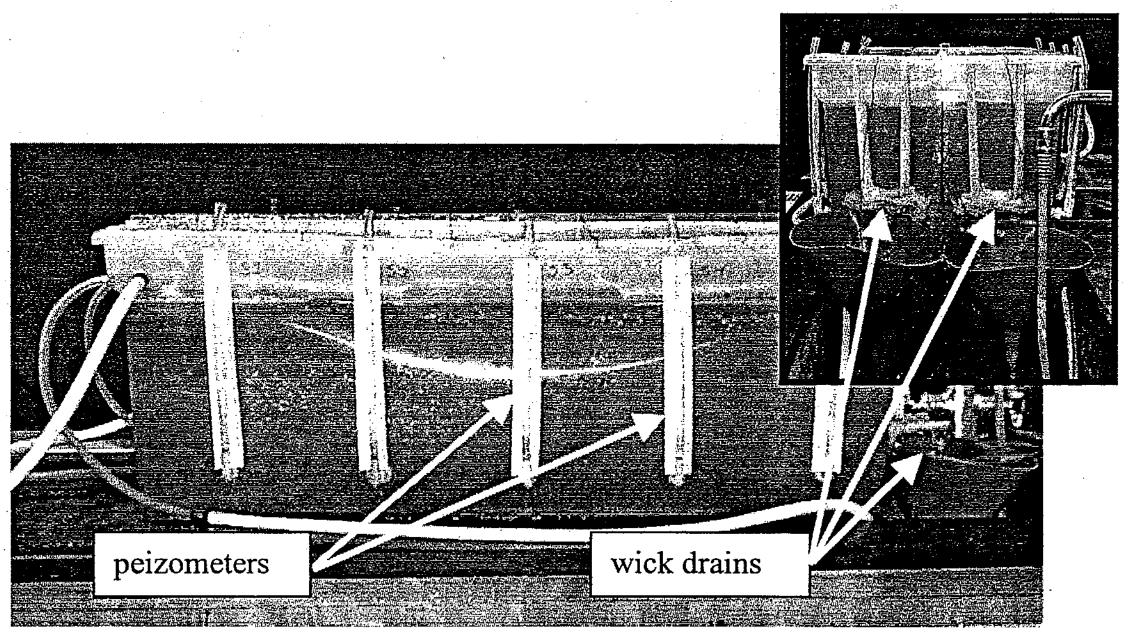

Figure 4. Laboratory test boxes containing wicks encased in soil with piezometers to measure water levels along the length of the wicks (inset shows front view).

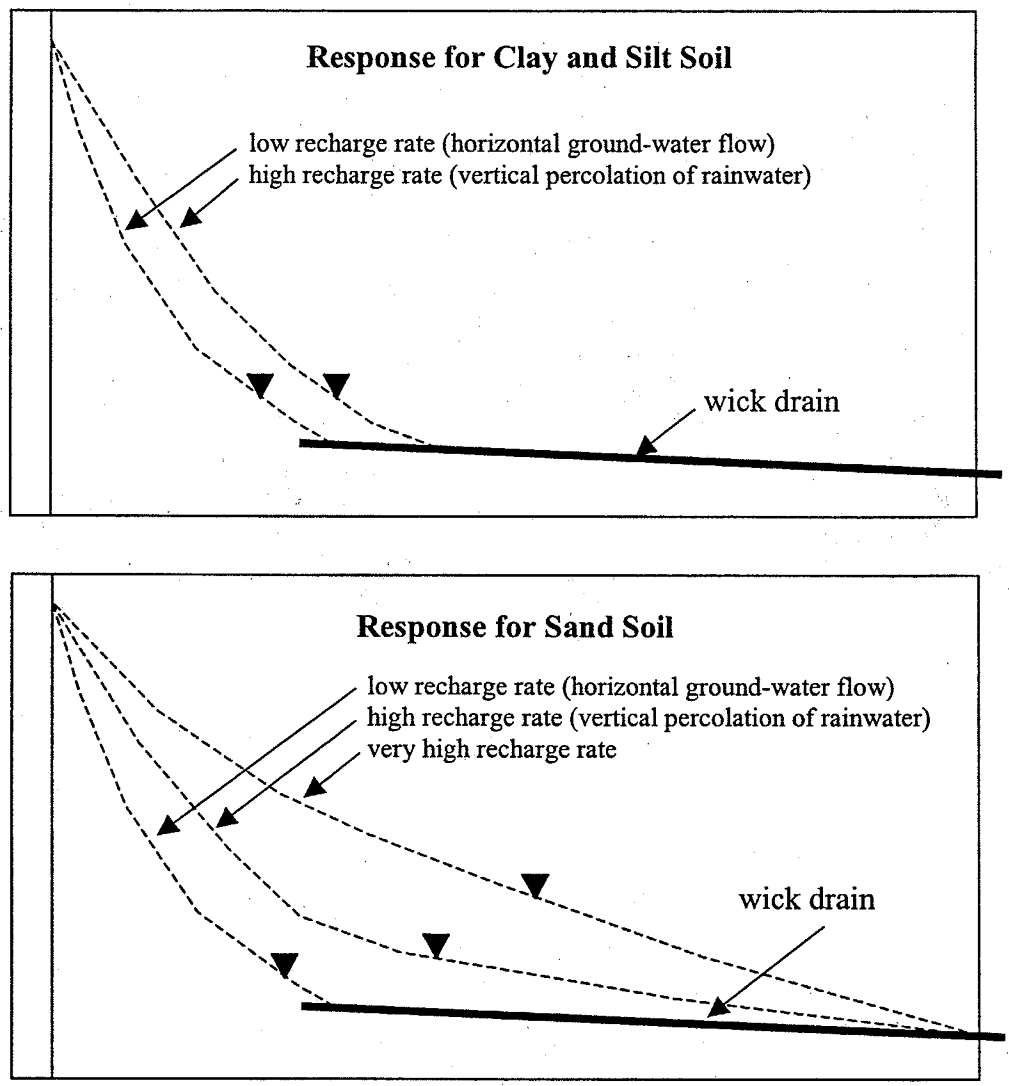

Figure 5. Schematic drawing showing the relative position of the water table observed in the laboratory test boxes shown in Figure 4. Water tables are shown by dashed lines.

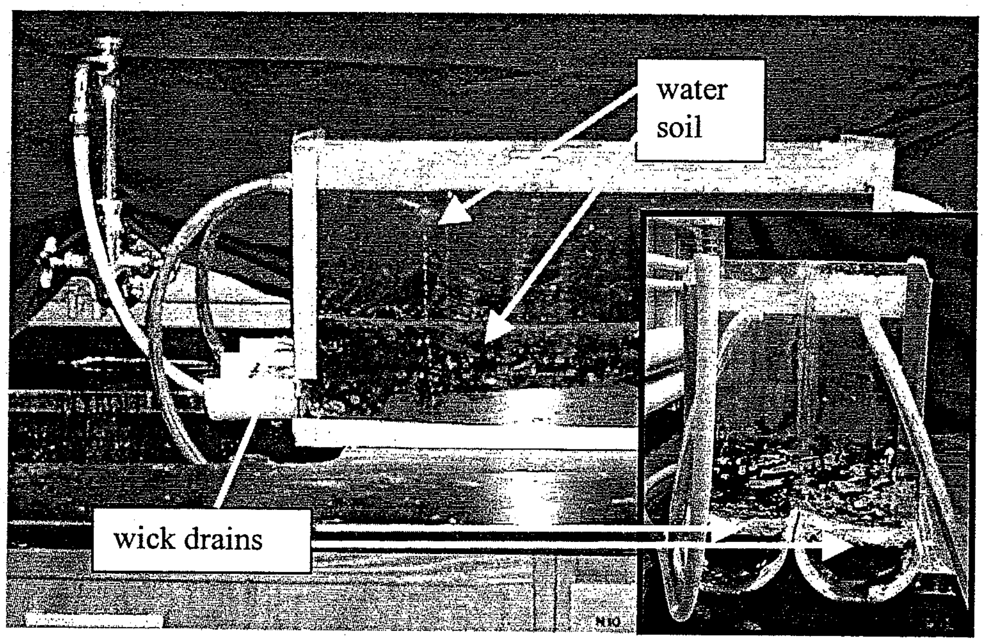

Figure 6. Laboratory test box used to text wick clogging over time (inset shows front view).

Figure 7. Photograph (30X) of new wick drain material that has never been placed in soil.

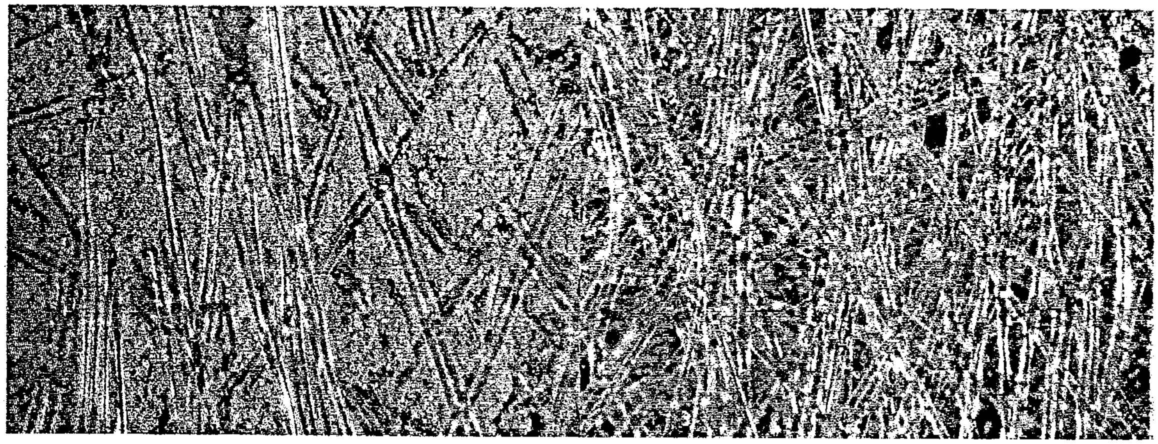

Figure 8. Photograph (30X) of wick drain material surrounded by clay soil for over two years. Left image is outside of filter and right image is inside of filter.

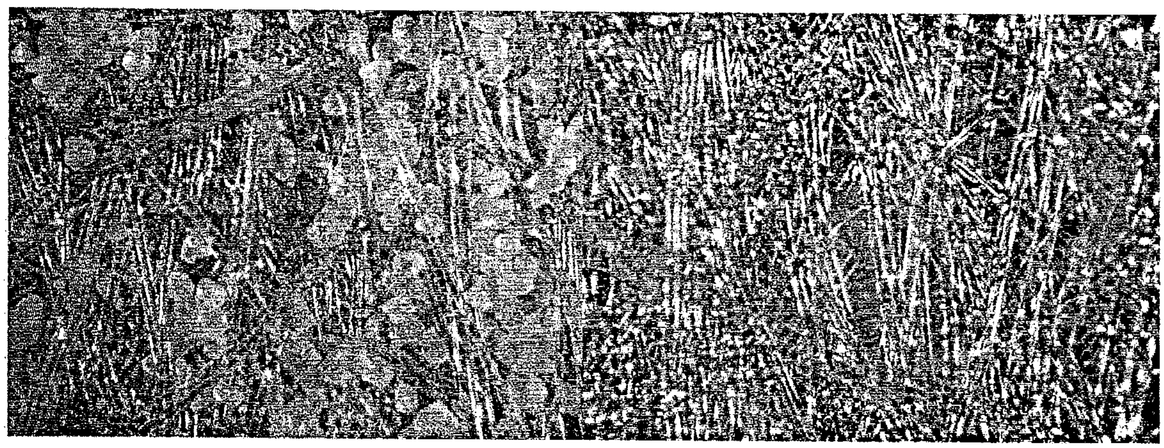

Figure 9. Photograph (30X) of wick drain material with a sand filter between the wick drain and the clay soil. Left image is outside of filter and right image is inside of filter.

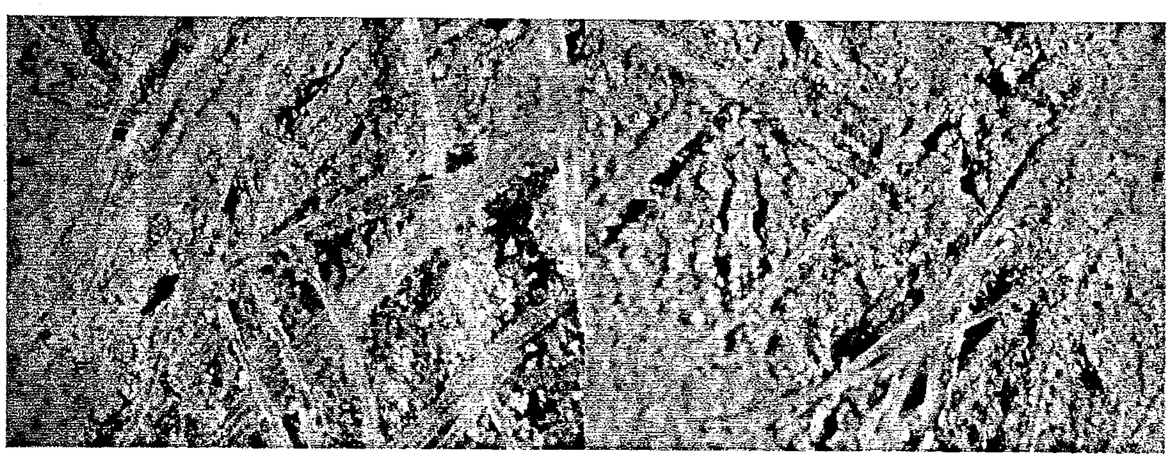

Figure 10. Photograph (30X) of wick drain exhumed from the Meeker, Colorado site two years after emplacement. Left image is outside of filter and right image is inside of filter.

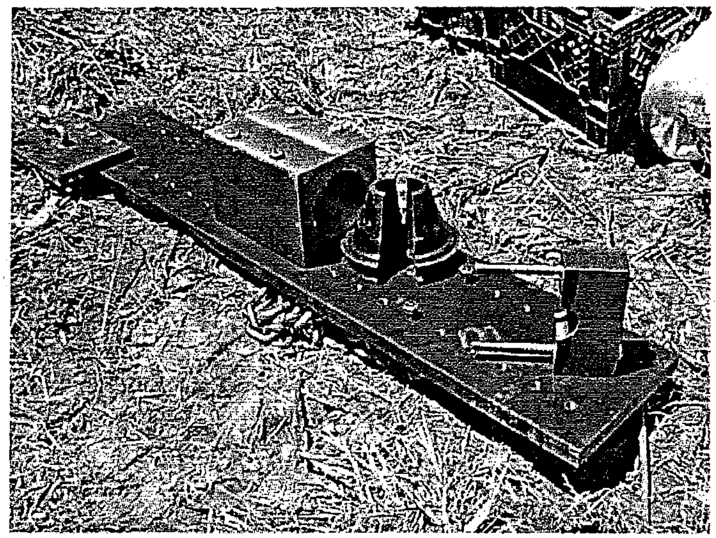

Figure 11. Pipe gripping mechanism.

Figure 12. Testing of pipe gripping mechanism using a backhoe.

Figure 13. Testing of pipe gripping mechanism using a motor grader.

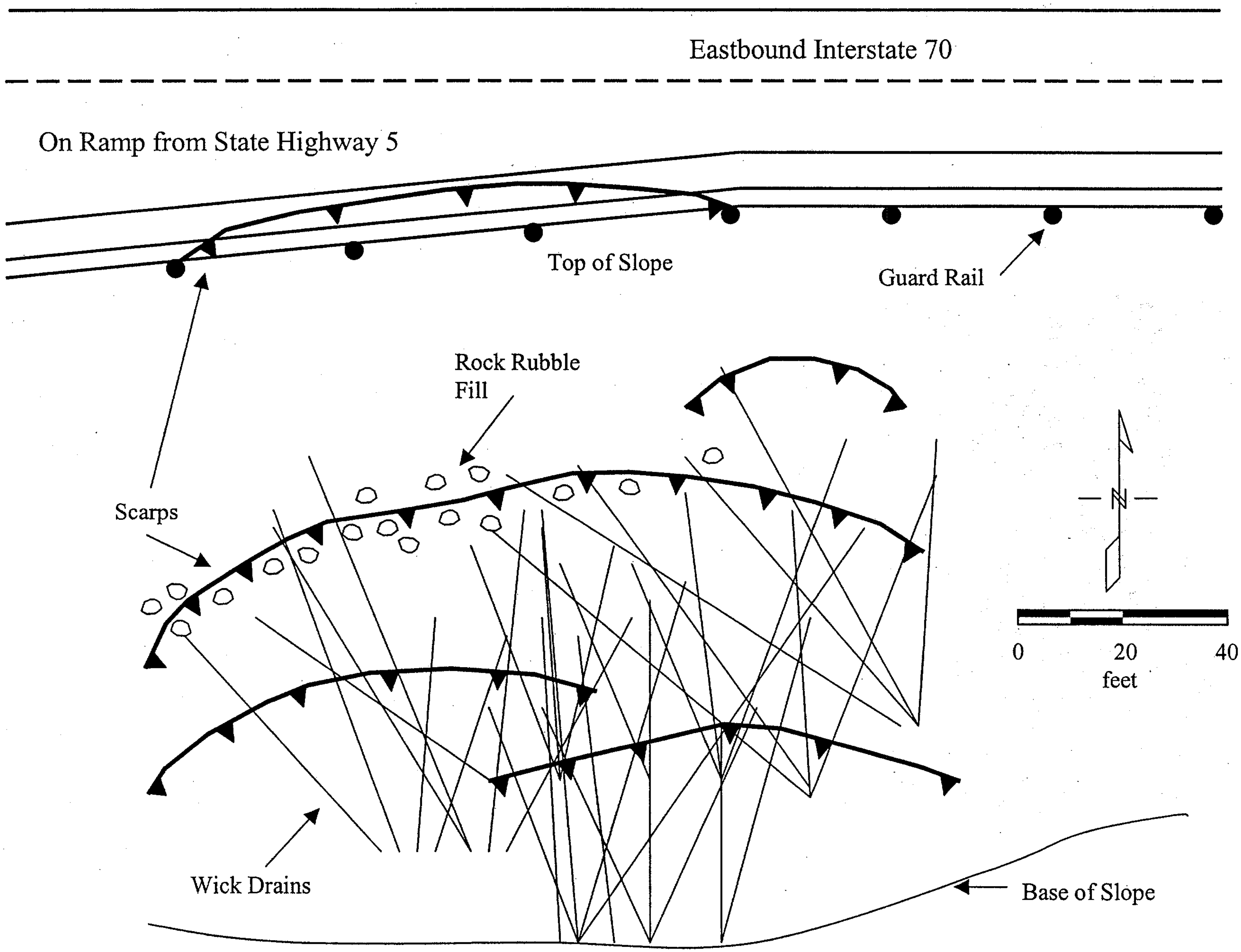

Figure 14. Map of landslide and drain locations, Boonville, Missouri.

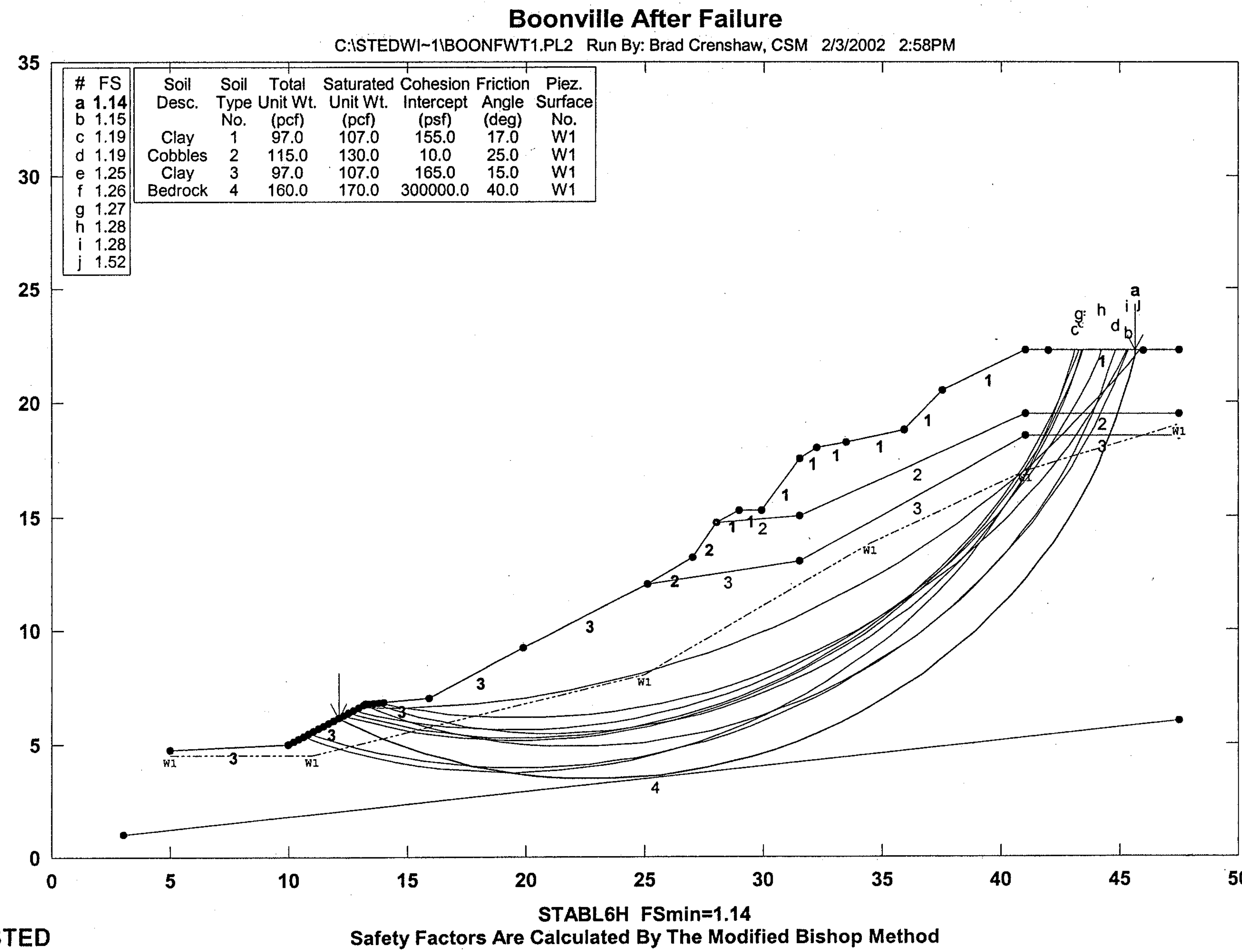

Figure 15. Stability at Boonville, Missouri under normal ground-water conditions.

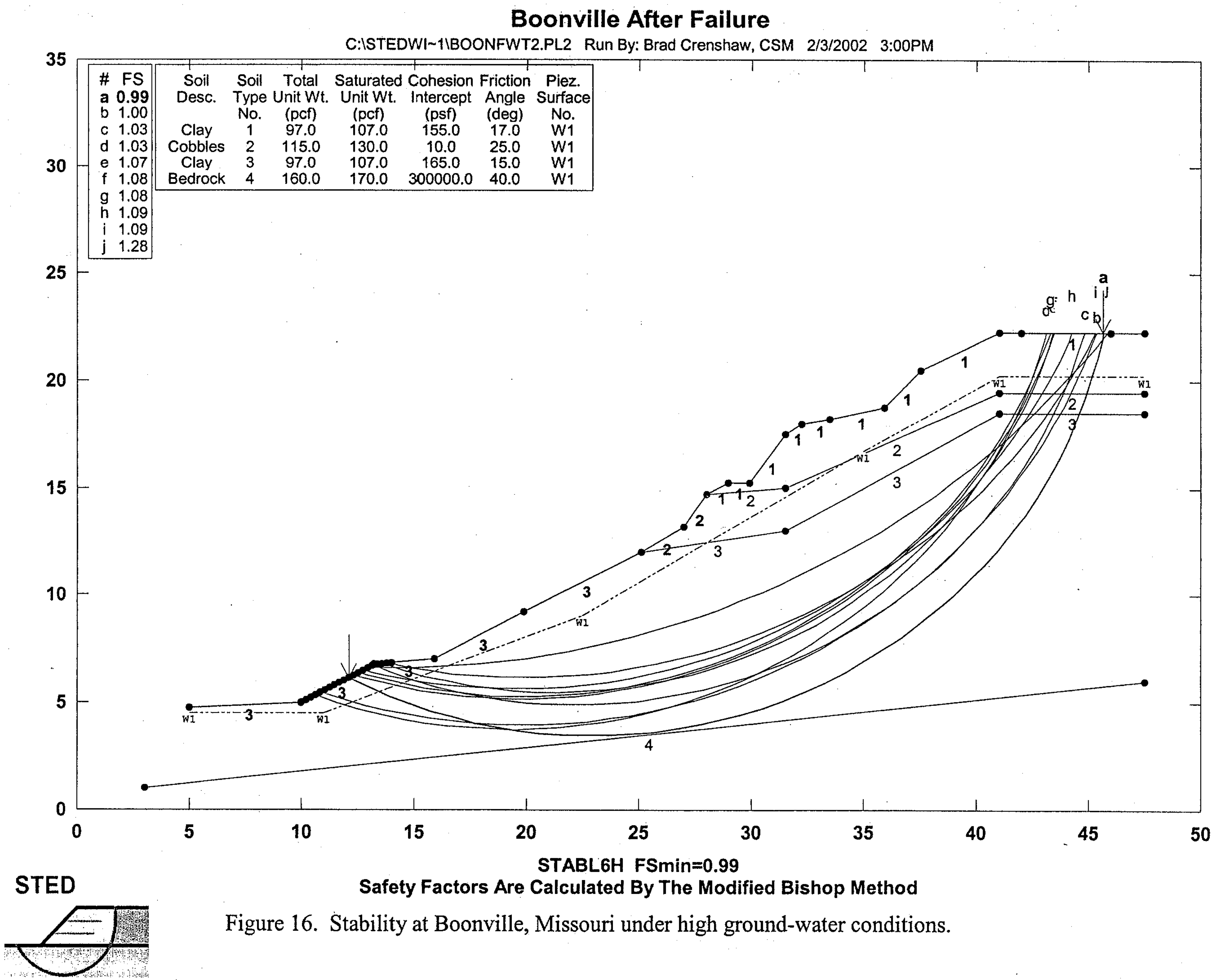

Figure 16. Stability at Boonville, Missouri under high ground-water conditions.

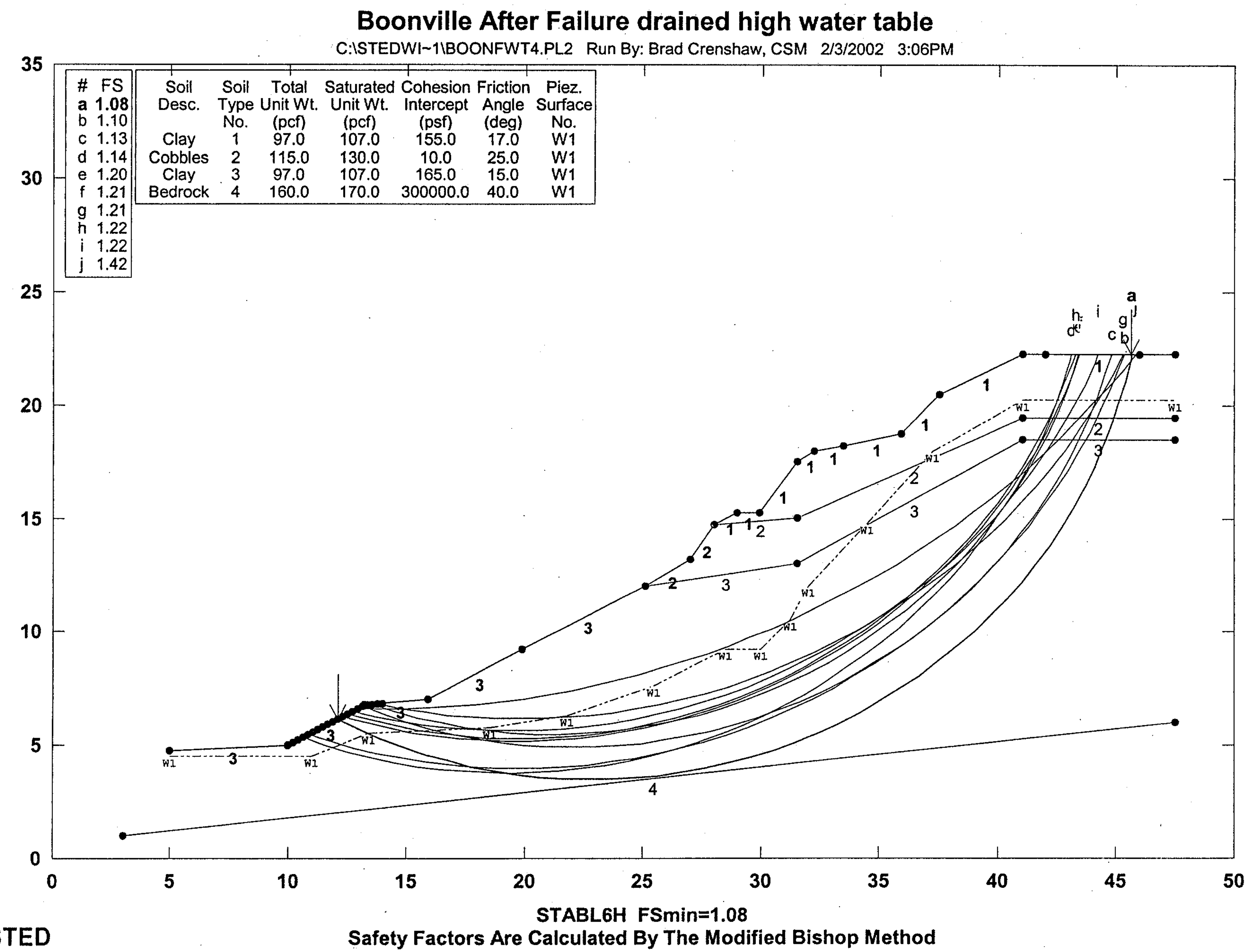

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Figure 17. Drained stability at Boonville, MO, under high ground-water conditions.

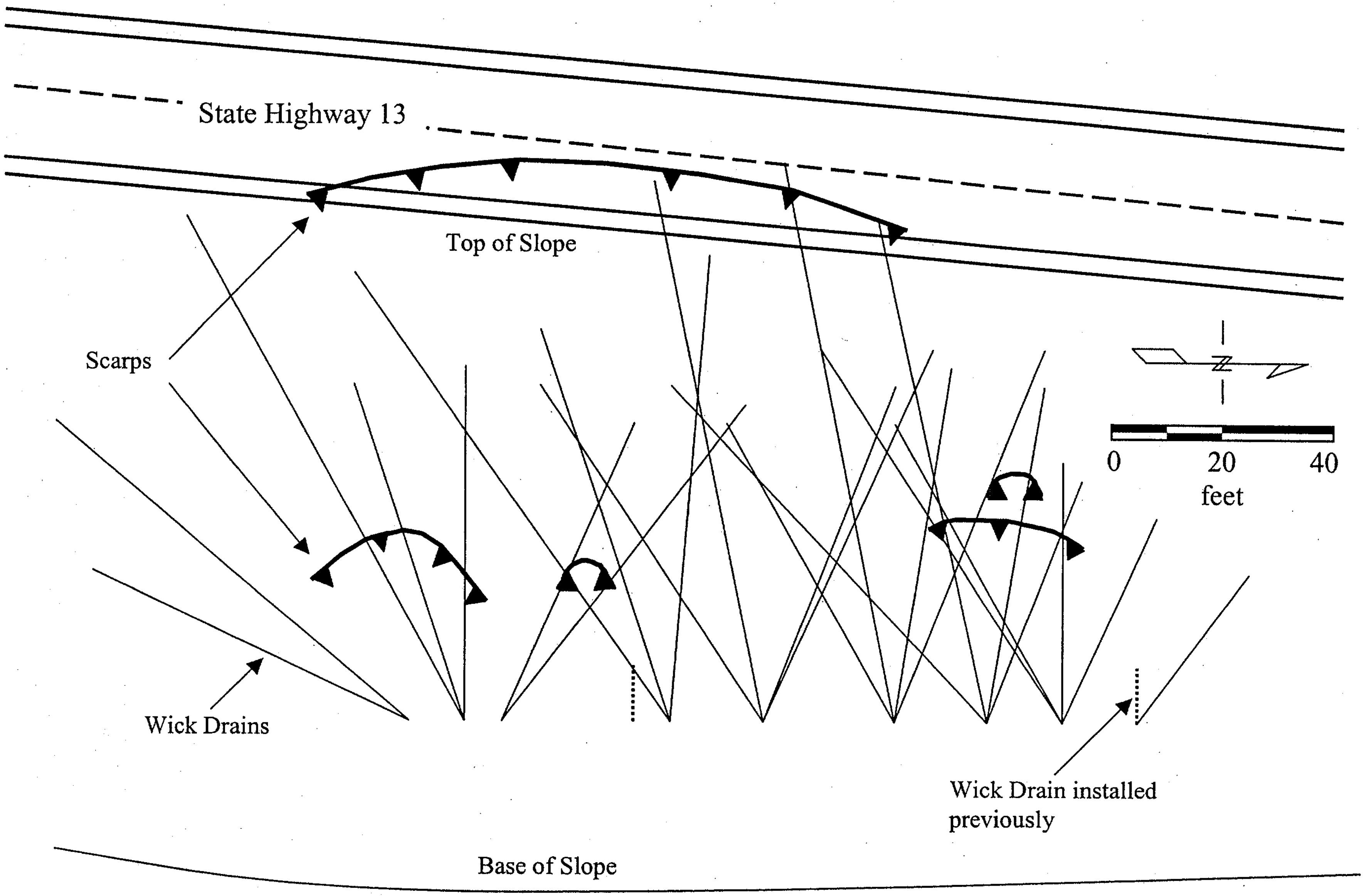

Figure 18. Map of landslide and drain locations, Meeker, Colorado.

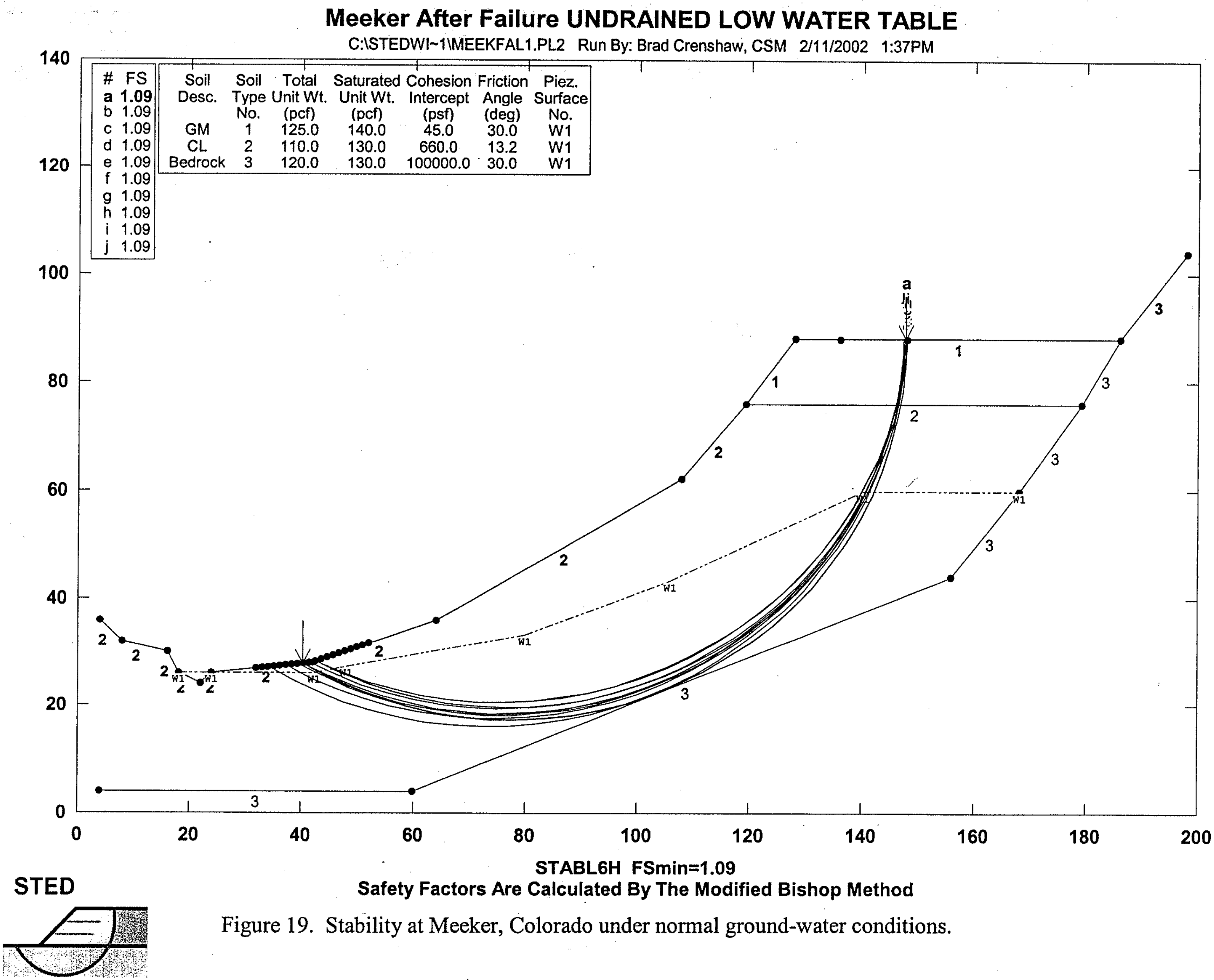

Figure 19. Stability at Meeker, Colorado under normal ground-water conditions.

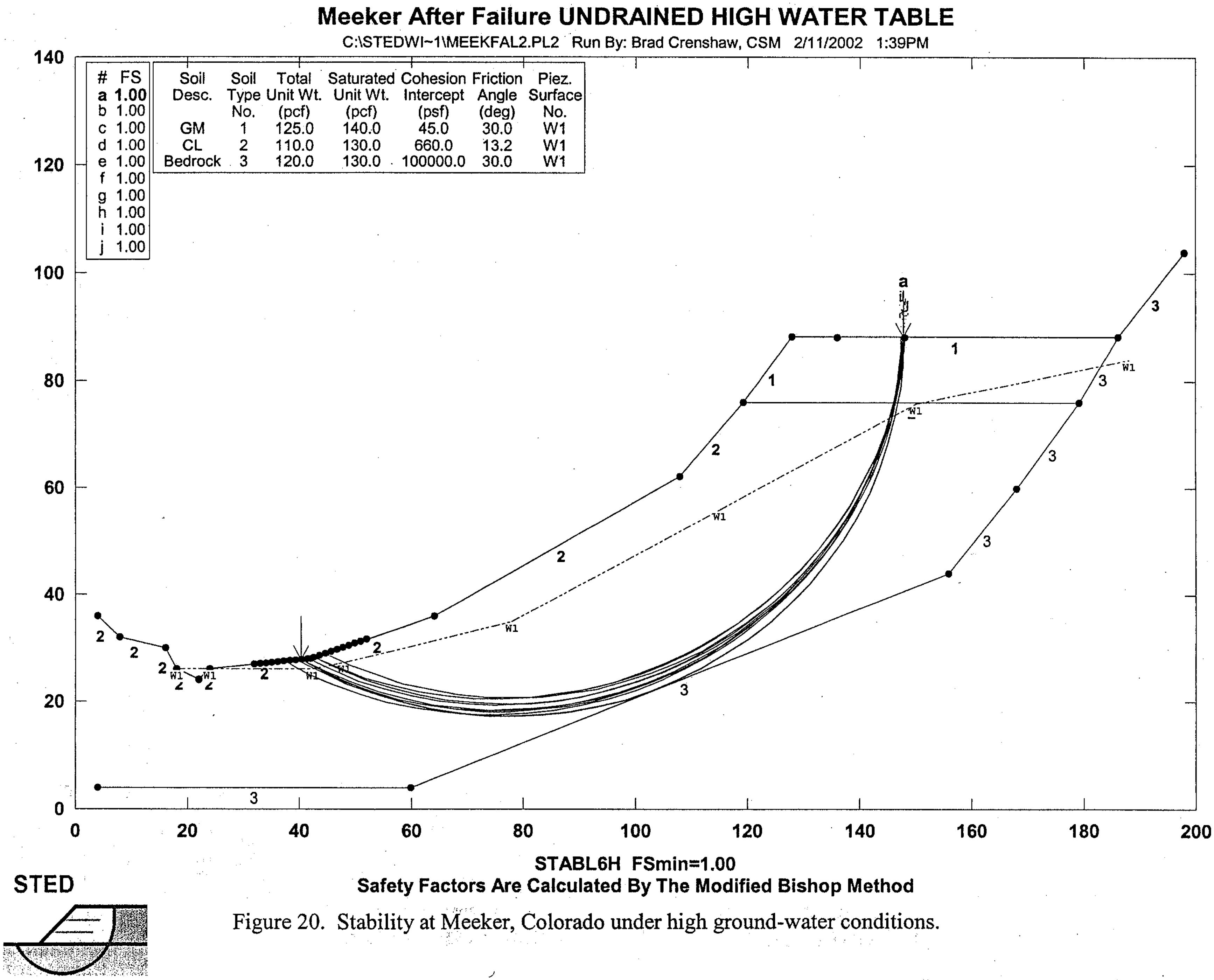

Figure 20. Stability at Meeker, Colorado under high ground-water conditions.

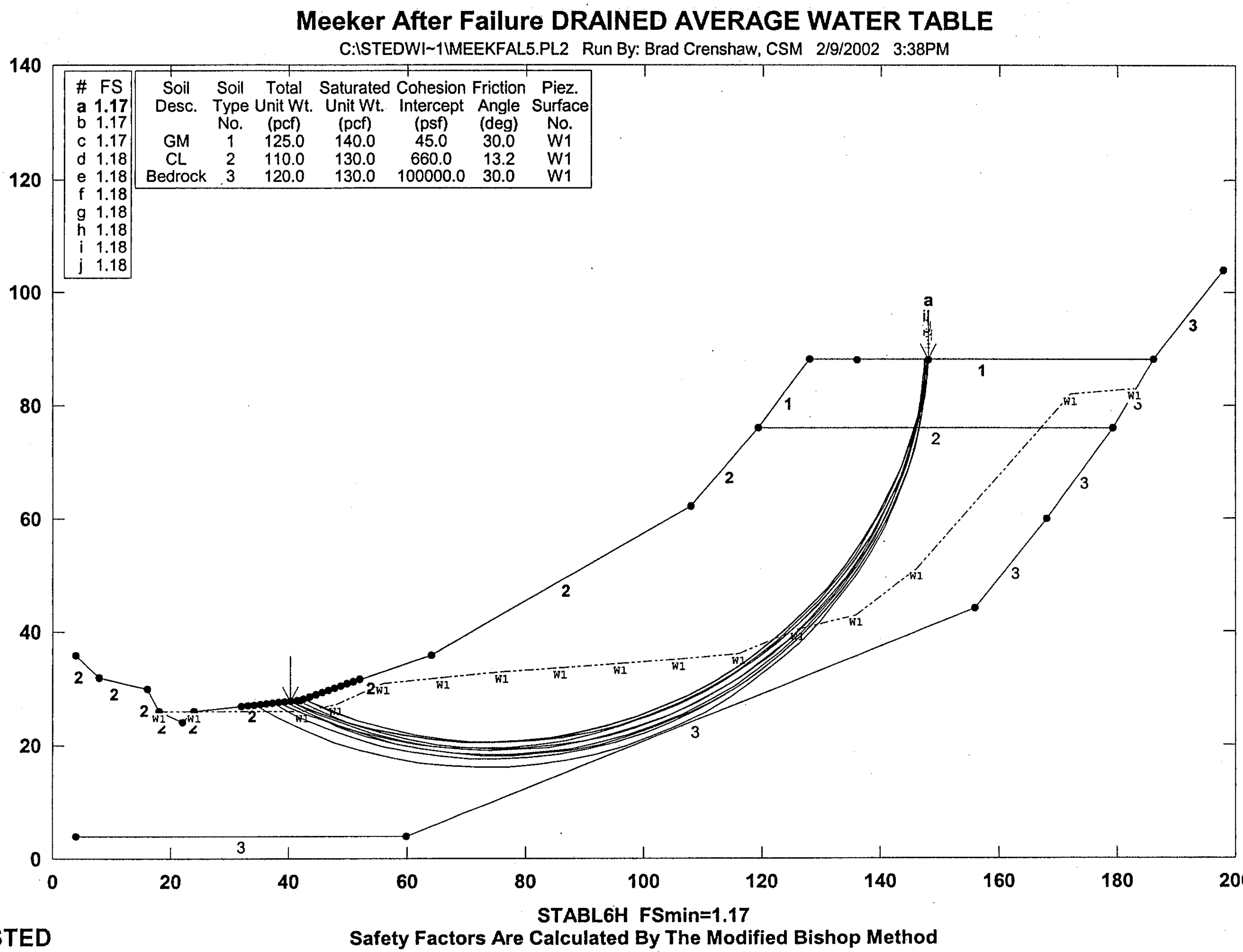

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Figure 21. Drained stability at Meeker, CO, under high ground-water conditions.